Geoindicators Scoping Report for Rocky Mountain National Park

Strategic Planning Goal Ib4

August 8-9, 2001
Estes Park, Colorado

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Geoindicator Scoping Summary

Introduction

A geoindicator's scoping meeting for Rocky Mountain National Park was held in Estes Park, Colorado on August 8-9, 2001. Participants included staff from Rocky Mountain National Park, U.S. Geologic Survey (USGS), the National Park Service's Geologic Resources Division (GRD), and other local geologists. This report summarizes the group's discussions and provides recommendations for physical studies to support resource management decisions, inventory and monitoring studies and research.

Purpose of Meeting

The purpose of the meeting was threefold: (1) to identify significant geological processes and features that affect or influence the park's ecosystem, (2) to evaluate human influences on those processes, and (3) to provide recommendations for studies to support resource management decisions, geologic inventory and monitoring projects, and research to fill data gaps. The scoping meeting was designed to use the participants' expertise and institutional knowledge of the park.

Government Performance and Results Act (GPRA) Goal Ib4

This meeting satisfies the requirements of the GPRA Goal Ib4, which is a knowledge-based goal that states, "Geological processes in 53 parks [20% of 265 parks] are inventoried and human influences that affect those processes are identified." The goal was designed to improve park managers' capabilities to make informed, science-based decisions with regards to geologic resources. It is the intention of the goal to be the first step in a process that will eventually lead to the mitigation or elimination of human activities that severely impact geologic processes, harm geologic features, or cause critical imbalance in the ecosystem.

Because GPRA Goal Ib4 inventories only a sampling of natural resource parks, information gathered at Rocky Mountain National Park may be used to represent other parks with similar resources or patterns of use, especially when findings are evaluated for Servicewide implications.

Geoindicator Background Information

An international Working Group of the International Union of Geological Sciences developed geoindicators as an approach for identifying rapid changes in the natural environment. The National Park Service uses geoindicators during scoping meetings as a means to fulfill GPRA Goal Ib4. Geoindicators are measurable, quantifiable tools for assessing rapid changes in earth system processes. Geoindicators evaluate 27 earth system processes and phenomena (Appendix A) that may undergo significant change in magnitude, frequency, trend, or rates over periods of 100 years or less and may be affected by human actions (Appendix B). Geoindicators are used as a framework to guide the discussion and field observations during scoping meetings (Appendix C) and are considered a proxy for geologic processes. The geoindicators scoping process for National Parks was developed to help determine the studies necessary to answer management questions about what is happening to the environment, why it is happening, and whether it is significant.

The health and stability of an ecosystem is evaluated during the geoindicators scoping process. The geologic resources of a park—soils, caves, streams, springs, beaches, volcanoes, etc.—provide the physical foundation required to sustain the biological system. Geological processes create topographic highs and lows; impact water and soil chemistries; influence soil fertility and characteristics, hillslope stability, and the quality and quantity surface water and groundwater. These factors, in turn, determine where and when biological processes occur, such as, the distribution of habitats, the productivity and type of vegetation, and the response of ecosystems to human impacts (Appendix D).

Park Selection

Rocky Mountain National Park was selected as a participant for geoindicators scoping because of its unique geologic resources and varied human uses (Appendix E and F). This park was also chosen because of its close proximity to the Denver area and the extensive geologic expertise available to the park.

Summary of Results

During the scoping meeting, geoindicators relevant to Rocky Mountain National Park, were identified and evaluated. Of the 27 geoindicators, 18 were recognized as on-going processes in the park. An additional geologic indicator, lake ice phrenology (first freeze/first thaw) that was not part of the original geoindicators list was also included. Participants rated the geoindicator with respect to the importance of the geologic process on ecological health and the influence of human activity on the geoindicator (table). Park staff rated the significance of the geoindicator for park management. A rating of high, medium, and low was used. A summary of the scoping session discussion are included in Appendix G. The summary notes highlight additional information regarding geoindicators that may be useful to park managers.

Geoindicator table for Rocky Mountain National Park

Geoindicator	Importance to Park Ecosystems	Human Influence on Geology	Significance for Management
Glacial and Periglacial			
Frozen ground activity	**H**	L	M
Glacier and firn field fluctuations	**M**	M*	M
Lake ice (ice phrenology)	**H**	**H***	**H**
Aeolian			
Wind erosion	**H**	L	M
Air borne sediment and deposition	L	**H***	M
Groundwater			
Groundwater quality	L	M	M
Groundwater level and springs	L	M	M
Surface Water			
Lake levels	L	L	M
Surface water quality	**H**	**H**	**H**
Stream channel morphology	**H**	**H**	**H**
Streamflow	**H**	**H**	**H**
Stream sediment storage and load	**H**	**H**	**H**
Wetlands extent, structure, and hydrology	**H**	**H**	**H**
Tectonics and Gravity			
Slope failure	**H**	M	**H**
Seismicity	L	L	L
Surface displacement	L	L	L
Soils			
Soil quality	L	L	L
Soil and sediment erosion	L	M	M
Other			
Sediment sequence and composition**	**H**	M	**H**

* Indicators of global climate change or land use activities outside the park boundary
H – HIGHLY influenced by, or with important utility for
M – MODERATELY influenced by, or have some utility for
L – LOW or no substantial influence on, or utility for

** Sediment sequences and composition is a tool with great significance for enhancing the information base of the park's ecosystem, identifying human influences on the ecosystem, and providing data for management decisions and planning.

Geoindicators with importance to park ecosystems

Of the nineteen geoindicators identified in the park, eleven were considered to be highly significant to park ecosystems. Five of the geoindicators were associated with surface water and were: surface water quality, stream channel morphology, streamflow, stream sediment storage and load, and wetlands. The other six geoindicators included: frozen ground activity, lake ice, wind erosion, slope failure and sediment sequence and composition.

Geoindicators with significant human influence

Geologic processes can be influenced by human activities through extraction of natural resources, alteration of natural processes, visitor use impacts, park management practices and developments, land use adjacent to parks, and global issues (e.g. industrial dust from China). Human induced changes can fall into two groups. There are changes that are irreversible, such as slope failures caused by trail and road construction, and those that are reversible, such as compacted soil. In order to manage ecosystems and natural resources, it is essential to have a fundamental understanding of how human activities impact or alter geologic processes.

Human influence on geologic processes was rated high for seven geoindicators. Five of the geoindicators were associated with surface water or stream processes, and were: surface water quality, stream channel morphology, streamflow, stream sediment storage and load, and wetlands. The long-term diversion of water from park streams by the Grand Ditch, the largest water diversion in the park, has significantly altered all these processes on park streams. Also, a catastrophic failure of a dam in the park resulted in extensive alteration of stream channels.

Human activities outside the park boundary are also potentially impacting park resources. Two other geoindicators were identified as highly influenced by human activities outside the park boundary; lake ice (occurrence of the first thaw and first freeze) and airborne sediment and deposition. Lake ice phrenology can be affected by global warming. Air borne sediment and deposition from both the eastern Front Range communities and global land use may be influencing the park. Although the park cannot directly affect a change on the human influence on these geoindicators, they are still considered high.

Geoindicators with high management significance

Geologic processes may have a high management significance due to safety concerns, administrative use of resources, or protection of fragile resources from detrimental human activities. It is important for park managers to be aware of what geologic processes are active in the park and how to adapt park management to address these processes. This knowledge can greatly assist managers in making decisions to protect human safety and natural resources.

Management significance was high for eight geoindicators. The surface water geoindicators that rated high for human influence also ranked high for management significance. Human activities have significantly altered surface water processes and consequently changed the natural processes occurring in the park. Park management is concerned with mitigating and rectifying these human influences.

In addition to the five surface water geoindicators, three other geoindicators (lake ice, slope failure and sediment sequence and composition geoindicator) also rated high for management significance. Slope failures can clearly be hazardous to humans and need to be monitored in order to protect visitors and park staff. Landslide processes also affect maintenance of park roads and trails. Sediment sequence and composition is a tool that can provide invaluable information to resource managers on on fire history, ecotones, and paleo-ecology and would provide an indication of the degree and nature of impacts of past events on the park. Sediment deposits also provide a baseline on which to compare contemporary environmental change.

Significant geoindicators

Particular attention is paid to those geoindicators with a high rating across all three categories; significance to the park's ecosystem, human influence or management significance. Six geoindicators rated high for all three categories and almost all were associated with surface water and stream processes.

Surface water quality
Because of the close proximity of the urban interface along the eastern Front Range, the Park's natural resources are affected by industrial airborne pollution, such as nitrates. Studies have linked pollution from the east side of the Colorado Front Range to increases in nitrogen in the park soils, streams, lakes and spruce trees, as well as, changes in lake diatom community composition over time. These have long term consequences to the park's fish and wildlife communities. Based on the results of studies conducted in the park, the Park Service is petitioning the Environmental Protection Agency to set higher air quality standards to protect the park's resources.

Stream channel morphology, Streamflow and Stream sediment storage and load
<u>Grand Ditch</u> **-**Water diversions for agriculture and urban use has significantly altered the streamflow, channel morphology and wetlands in the park, most notably in the upper Colorado River in the Kawuneeche Valley. The ditch intercepts about one-third of the total annual runoff to the upper Colorado River and has reduced lower magnitude peak flows by more than half and altered sediment transport. As a result, the frequency of overbank flooding and channel maintenance flows have been reduced and the channel has adjusted its channel dimensions and morphology to the altered hydrologic regime. Human alteration of streamflow and sediment transport of the upper Colorado River has affect channel geometry and morphology and has long-term impacts on the park's aquatic and riparian ecosystems.

<u>Hidden Valley Ski Area</u> - The stream channel in the Hidden Valley Ski Area was buried and culverted during construction of the lodge. For several decades, the Hidden Valley Ski Area also captured and diverted all streamflow in the watershed for making artificial snow. Human alteration of streamflow and channel alterations in this watershed caused significant impacts to the aquatic habitat within and downstream of the ski resort. Endangered greenback cutthroat occupy the channel downstream of this site. The park must manage and protect Threatened and Endangered Species and will be restoring the stream channel and aquatic habitat. In the future, restoration of the stream and associated wetland at the Hidden Valley Ski Area will occur after the ski lodge and parking lot are

removed. Most of the buildings have been demolished and the Environmental Assessment has been reviewed by the public.

Lawn Lake Flood - A catastrophic failure of a dam in the Roaring Gulch Valley resulted in significant long-term changes in channel morphology and sediment storage and load to both the tributary valley and in Fall River.

Wetlands extent, structure and hydrology
Diversion of surface water flow has resulted in decreased groundwater to some toe slope wetlands and peatlands in the Kawuneeche Valley. The change in groundwater level has caused changes in wetland vegetation, establishment of exotic dryland plant species, and the net loss of carbon from selected peatlands. Studies indicate that some of the peatlands in the Kawuneeche Valley may not be sustained over the long-term based on the lowered groundwater levels caused by water diversions. This may ultimately lead to the disappearance of peatlands in areas of the valley. The park is concerned with protecting the existing aquatic and wetland habitat from further decline.

Lake ice
Global climate change occurs naturally, but human activities can accelerate the process. Monitoring the first thaw/first freeze of park lakes, provides an early warning of global warming. While the park cannot addressing the global warming issue through its management it is useful to understand when impacts are occurring.

Summary of Recommendations

The following summary of recommendations lists ideas discussed during the August 8-9, 2001 scoping meeting held in Rocky Mountain National Park. The summary includes recommendations for inventory, monitoring and research studies, as well as, recommendations for specific management issues, public education and planning.

Surface water geoindicators should be considered as candidates for monitoring or further inventory and study because of the overall high rating of significance for the surface water geoindicators. At a minimum, the park may want to consider gathering further information about these geologic processes. If the park would like to pursue some of these recommendations, needs geologic expertise, or help interpreting the significance of geologic studies to the park contact Bob Higgins, Chief of Science and Technical Services Branch, Geologic Resources Division, NPS; (303) 969-2018; e-mail: Bob_Higgins@nps.gov.

Recommendations for inventory

1. Map areas of frozen ground activity
Identify permafrost processes and map areas of frozen ground activity in the park. Landscapes with frozen ground activity (gelifuction) can create significant engineering and maintenance problems for facilities, roads, trails, and septic systems. Maps will be useful for future planning and placement of park infrastructure, and developments.

2. Inventory park glaciers
Map and inventory the extent, quantity, size (length and depth) of glaciers in the park. An inventory of glaciers is in progress, but the project is significantly underfunded.

3. Evaluate importance of melting snowfields and glaciers to annual runoff
Contact agencies in charge of monitoring snow pack to determine the types of data collected and if predictions of annual runoff include melt water from snowfields and glaciers in the park. Determine the importance of these sources of water to both streamflow and annual runoff to park streams.

Recommendations for monitoring

1. Track regional alpine studies
The park should investigate and track several regional alpine studies located in the Colorado Front Range near Rocky Mountain National Park. These studies can provide local baseline data and long-term trends associated with glacial fluctuations and frozen ground activity. Potential programs to investigate are studies at Niwot Ridge Long Term Ecological Research Program in Colorado (http://www.colorado.edu/mrs/), monitoring at Indian Peaks (University of Colorado) and Lock Vale (USGS) and research by the Institute for Alpine and Arctic Research (INSTAAR). These agencies and programs can also provide standardized techniques and established protocols for monitoring alpine processes related to the geoindicators at Rocky Mountain National Park.

2. Determine the depth and thickness of the permafrost and monitor the rate of creep
Creep rates combined with the maps of frozen ground area (see project above) would be useful to the park's Maintenance Division and park planners. If creep rates change overtime, the park can evaluate what potential effects might occur to park infrastructure and resources. Frost tubes can be used to monitor rates of movement and can be calibrated with monitoring studies at INSTAAR.

3. Establish long-term stream gaging stations on selected park streams
Establish baseline flow data for park streams. Long-term flow data can be used to monitor potential changes in surface water supply.

4. Monitor dust deposition in the park
Utilize dust traps following standardized protocols developed by the USGS and determine source areas for particulate matter. A study is currently in progress. Incorporate dust monitoring into the existing air quality monitoring program.

5. Develop a baseline groundwater quality monitoring program

Contact:

- Dan Kimball, Water Resources Division, NPS,
  e-mail:dan_kimball@nps.gov, (970) 225-3501

6. Establish a lake-level monitoring program
Determine the seasonal variability of lake levels. Install staff plates in selected lakes. Use park staff as observers to periodically record lake levels.

7. Monitor lake ice phrenology
Establish monitoring of ice phrenology on park lakes. Determine the date of first freeze and first thaw for alpine lakes to track the effects of global climate change at in the park. Develop baseline data to track long-term climate change.

Recommendations for research

1. Determine former locations of treeline/tundra interface
The treeline/tundra interface is an important marker for understanding paleoclimates. Treeline position may be a better indicator of climate change than monitoring glacier fluctuations. Determine the location of former treeline/tundra ecotone and evaluate what controls its position in the park.

2. Determine long-term trends in glacial ice volumes
Develop a glacial budget and quantify the amount of ice accumulating, ablating, and sublimating (gains and losses) from park glaciers. A study is currently in progress, but is significantly underfunded.

3. Quantify the dust component of the airborne particulate matter in the park
Determine the origin of airborne dust; that is, local (eastern Front Range communities) or global source. Also determine if there is a relationship between the amount of dust deposition and nitrate concentration.

4. Determine fire history, ecotones and paleo-climate information from sediment cores
Obtain sediment cores from selected lakes, marshes and wetlands in the park. Analyze the chemical, physical and biological character of aquatic sediments to provide fire history, ecotones, and paleo-climate information. A study is currently in progress, but needs additional funding to complete the project.

5. Geomorphic analysis to evaluate recent changes in channel morphology of the upper Colorado River in the Kawuneeche Valley
Determine the peak flows and channel maintenance flows necessary to restore the function of the upper Colorado River and associated riparian areas.

Recommendations for park management issues

1. Develop restoration strategies for stream and wetlands at Hidden Valley Ski Area
Consult with the NPS Water Resources Division for restoration strategies for the stream and wetland at the Hidden Valley Ski Area. It is important to replicate the channel gradient and channel dimension rather than the exact location of the original stream.

Contact:

- Dan Kimball, Division Chief, Water Resource Division, NPS
  Dan_Kimball@nps.gov, (970) 225-3501.

2. Monitor stream channel and wetland response to restoration work
Develop a monitoring program to quantify the response of the stream channel and wetlands restoration at Hidden Valley Ski Area.

3. Monitor channel changes in response to removal of check dams
The park has an active program of removing old or failed check dams. Quantify channel changes and stream response to removal of check dams on park streams.

4. Review all existing and potential trails for slope stability and erosion potential by geologists
The park should work with geologists to identify the best location for to route trails that cross hazardous areas (areas of high potential slope failure). It is recommended that the park work with the GRD to coordinate this project with USGS geologists.

Contact:

- Bruce Heise, Geologist, Geologic Resources Division, NPS.
  Bruce_Heise@nps.gov, (303) 969-2017

5. Develop a slope failure map
Identify locations, landslide process, and develop a risk analysis for parklands. In the interim, a slope stability map can be derived from the existing geologic maps by Colton (1976) and Braddock and Cole (1990). The park should work with the GRD to coordinate this project with the USGS.

Contact:

- Bruce Heise, Geologist, Geologic Resources Division, NPS.
  Bruce_Heise@nps.gov, (303) 969-2017

6. Develop snow avalanche risk maps
Determine if snow avalanche areas have been mapped in the park by the Colorado Avalanche Information Center or INSTAAR. Develop snow avalanche risk maps for roads, trails, developments, and facilities.

7. Continue to make progress on water rights issues in the park.
The Grand Ditch is a major detriment to re-establishing natural hydrologic processes and conditions in the upper Colorado River. The park should continue to gain water rights by buying existing water rights where feasible and retiring them, pursuing alternative strategies for obtaining water rights, and investigating mitigation measures to minimize the impacts associated with the diversion of water from the Colorado River watershed.

Recommendations for public education

The diverse landscape at Rocky Mountain National Park provides an exceptional opportunity to interpret the natural processes that have created the outstanding geologic features in the park. The underlying geology forms the foundation of the park's ecosystems and geologic processes continue to shape and modify the park's landscapes.

1. Develop a geology Frequently Asked Questions sheets
It would be useful to develop Frequently Asked Questions sheets about geology for the seasonal training interpretive binders. Current geologic research could also be translated into a more useable format for interpreters to use. These types of materials could be developed by a Geoscientist-in-the-Park (GIP) coordinated by the Geologic Resources Division.

Contact:

- Judy Geniac, GIP Program Manager, Geologic Resources Division, NPS
  Judy_Geniac@nps.gov, (303) 969-2015

2. Interpretation of park geology
The park should consider "outreach" into the geologic community at the USGS, as well as, geologists working in the Denver area. USGS and local geologists who attended the meeting volunteered to train park staff at interpreter training and developing geologic interpretive information for seasonal training binders. Geologists could provide an overview of the geologic setting, points of interest, and significant geologic features in the park. The GRD may also be able to help assist in partnering professional geologists with the park.

3. Peer review of geologic interpretive information
A process should be developed so that geologic interpretive information is peer reviewed by appropriate scientists to verify the accuracy of the information before being released to the public. The GRD could facilitate outside reviews by appropriate organizations and individuals.

Recommendations for park planning

1. NPS planning process
The park is urged to incorporate geologic information provided in this report into appropriate planning documents, such as the General Management Plan, the Visitor Enjoyment Resource Protection Plan and the Resource Management Plan.

2. NPS Vital Signs Monitoring Program
Inventory and monitoring studies identified in this report should be considered when identifying indicators for vital signs monitoring in the networks and integrated with biological studies. These studies should also be considered essential for establishing baseline conditions and long-term monitoring in the park. Contact the GRD to coordinate geologic input for the vital signs monitoring program.

Contact:

- Bob Higgins, Chief of Science and Technical Services Branch, Geologic Resources Division, NPS; Bob_Higgins@nps.gov, (303) 969-2018;

References

Braddock, W.A. and Cole, J.C. 1990. Geologic Map of Rocky Mountain National Park and Vicinity, Colorado. Miscellaneous Investigations Series Map I-1973. 2 sheets.

Colton, R.B., Holligan, J.A., Anderson, L.W., and Patterson, P.E., 1976, Preliminary map of landslide deposits in Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-964, scale 1:500,000.

Meeting Participants

Rocky Mountain National Park
Ken Czarnowski, Chief, Resource Management and Research
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Darwin Spearing, Interpreter
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Appendices

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B. **Human Influences**
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Appendix A. Descriptions of 27 Geoindicators

Appendix B. Human Influences

Appendix C. Introducing Geoindicators

Appendix D. Species Don't Stand Alone—Geology's Role and Importance in Ecosystems

Appendix E. Park Setting and Resources

Setting

Rocky Mountain National Park was formed by a series of granitic batholiths intruded into Precambrian micashists and pegmatites. The Continental Divide passes roughly through the middle of the park dividing it into two distinct sides. Steep cliffs characterize the eastern slope with U-shaped valleys created by Pleistocene glaciation. The east slope sits in a slight rain shadow receiving about 15 inches of precipitation annually, and is subjected to high Chinook winds throughout the winter. In the west, the mountains along the Continental Divide fall away more gradually to the Kawuneeche Valley, and the Never Summer Mountains preserve the story of a volcanically-active past. The western slope receives about 20 inches of precipitation annually with deeper winter snows than the eastern slope.

Vegetation

Because of its great variations in elevation, soils, and climate, Rocky Mountain National Park is something of a botanical crossroads, with nine distinct floras ranging from ponderosa pine and grass/shrub meadows to alpine tundra. About 1,025 vascular plants have been identified in the park. Most of the vegetated landscape is dominated by forests such as ponderosa pine, lodgepole pine, and spruce/fir, or by non-forested alpine tundra.

Roughly 60% of the park is forest, 13% alpine tundra, 18% exposed rock and 9% a mixture of other habitat types. Major vegetation types consist of ponderosa pine and grass/shrubland habitat from 7,800 to 8,500 ft, lodgepole pine from 8,500 to 9,500 ft, spruce/fir from 9,500 to 11,500 ft, and alpine tundra over 11,500 ft. The west side of the park is characterized by lodgepole pine and spruce/fir. The west side of the Kawuneeche Valley leads up to the majestic Never Summer Mountains. The Continental Divide lies mostly to the east of the valley. The Kawuneeche Valley is about 9 miles long and ½ mile wide and is composed of marshes, bogs, ponds, and wet meadows dominated by sedges and willows.

Human and Natural Disturbance

Prior to the establishment of Rocky Mountain National Park, numerous human-caused disturbances occurred on sites now within the park. The disturbances varied considerably as to type, intensity, and duration of disturbance, but disturbances in the Colorado River District included mines, homesteads, sawmills, roads, settlements, lodges, cabins, camps, livestock grazing, haying and water diversion. Some of these disturbances (e.g. logging, mining and ranching) occurred in the Kawuneeche Valley, beginning in the 1870s. Logging and most mining operations ended by 1920, but ranching continued into the 1930s. Some disturbances such as water diversion are still occurring.

The Grand Ditch, which is the biggest water diversion in the park, located in the Colorado River District, is significantly impacting the North Fork of the Colorado River and its associated wetlands in the Kawuneeche Valley (Woods, 2000). The ditch was constructed in part from 1894 to 1935, and traverses the Never Summer Mountains in Rocky Mountain National Park for a distance of about 17 miles. It is entitled to divert up to 524.6 cubic feet per second of water under a water right with a priority date of September 1, 1890, 25 years before the park was established.

The Grand Ditch is still in operation, but many of the other early disturbances have been removed and the areas restored to natural conditions. The Never Summer Ranch was left intact in the Kawuneeche Valley, which provides visitors with an opportunity to view a ranch as it might have looked in the late 1800s. The buildings are open to the public in the summer but closed in the winter.

About 1% of the land in the park is now considered heavily disturbed. These areas include roads, frontcountry campgrounds, visitor centers, employee housing, utility areas and private inholdings. About 95% of the land in the park is roadless and either is recommended for wilderness or is already designated wilderness.

Appendix F. Park Geologic Setting

Geologic History

The diverse landscape at Rocky Mountain National Park displays some of nature's finest handiwork. Natural forces operating over nearly 2 billion years created geologic features that provide a fascinating glimpse into the mysteries of the park's evolution and clues to the continuing changes that shape the future of this dynamic environment.

Most of the rocks in Rocky Mountain National Park originally were deposited as shale, siltstone, and sandstone in an ancient sea about 1.8 to 2 billion years ago. Between 1.7 and 1.6 billion years ago, these sedimentary rocks and some interlayered volcanic rocks were deformed during a slow collision between sections of the Earth's crust called tectonic plates. These rocks, which formed the core of an ancient Proterozoic mountain range, were recrystallized into metamorphic rocks called schist and gneiss by enormous heat and pressure resulting from the collision and the depth of burial.

Some granites found in the park intruded at about the same time as the metamorphism and may have supplied some of the heat that caused the mineral transformations in the ancient marine sediments. About 300 million years later (1.4 billion years ago), the widespread Silver Plume Granite intruded upward into the metamorphic rocks and squeezed them into flat-lying positions as the molten granite flowed along planes of weakness in the metamorphic rock. Prominent cliff exposures along the east side of the continental divide (and especially around Longs Peak) show the intricate pattern of granite intruded layer-on-layer into the banded metamorphic rocks. The Silver Plume Granite is typical of other granites that intruded North America in a zone between southern California and Labrador about 1.4 billion years ago, probably in response to widespread melting in the mantle caused by a change in the mantle structure.

Little is known about geologic events in this area during the period from approximately 1,300 million to 500 million years ago because no rocks of that age are preserved. We infer that the ancient mountain ranges that formed during the metamorphism and the Silver Plume event were slowly eroded and planed down to a fairly flat surface, exposing the core of once-deep-seated metamorphic rocks and granite. About 500 million years ago, shallow seas covered this region and remained for nearly 250 million years as thousands of feet of Paleozoic sediment were slowly deposited.

During the middle Pennsylvanian Period, tectonic forces fractured the North American continental crust and, in this area, caused the uplift of another mountain range, called the ancestral Rocky Mountains. The seas receded, the mountain uplifts were eroded, and sediments shed from them were deposited by braided river systems along the mountain margins. These river deposits make up the Fountain Formation, which is prominently exposed today in the Flatirons west of Boulder, in the spectacular walls of Red Rocks Park at Morrison, and in the vertical red spines in the Garden of the Gods near Colorado Springs. We know that the erosion of the ancestral Rocky Mountains was deep because most of the older Paleozoic strata were stripped off and the Fountain Formation was deposited on a new planed-off surface of the ancient granitic and metamorphic basement.

Additional sediments were deposited on the land surface and offshore as the seas returned to the area of Rocky Mountain National Park between the middle of the Permian Period and the end of the Cretaceous Period, spanning the interval between about 260 and 65 million years ago. This time period covers most of the Mesozoic Era when animals began living on the land surface and when the dinosaurs evolved to take advantage of diverse habitats. Abundant bones and tracks in the Rocky Mountain region surrounding the park provide some of the best records in the world of the evolution and behavior of dinosaurs during those periods.

Major tectonic plates of the Earth's crust slowly collided along the western edge of North America during the late Mesozoic. This collision produced broad mountain-block uplifts in the area of the present Colorado Rockies beginning about 70 million years ago and caused the great inland sea to recede again. As the mountain blocks rose, many of them were pushed out over the surrounding basin deposits along low-angle thrust faults. This kind of relation is preserved in the park in the Never Summer Mountains where the Proterozoic crystalline rocks above the Never Summer thrust sit on top of the Pierre Shale and the early Tertiary Coalmont Formation.

As with previous episodes of mountain uplift, erosion once again cut down into the Proterozoic basement of the region and stripped away younger deposits. The gross form of the park's mountain setting in the Front Range uplift was established by the early Tertiary tectonic events. Further uplift occurred along the same general trends, and continues today, although at much slower rates.

Volcanic eruptions in the Never Summer Mountains between 29 and 24 million years ago spread lava and ash over the landscape. The tops of the volcanoes probably stood several thousand feet higher than the present mountain peaks, but all we see preserved today in the Never Summer Mountains are the eroded granitic roots of the volcanoes. Much of the erupted volcanic material was also eroded away, but relics remain in the northwest corner of the park at Specimen Mountain, Lava Cliffs, and Milner Pass on Trail Ridge Road.

Though the geologic origins of the park date back nearly two billion years, the shapes of the lofty peaks that characterize the park today are relatively young. The glaciers that gouged the granite faces of Longs Peak, Sundance Mountain, and Tanima Peak were formed approximately 10,000 to 15,000 years ago during the last major ice age. About 2 million years ago, Earth's climate cooled and the Ice Age began. The high mountain valleys filled with glaciers. Glaciation in the park probably started about 1.6 million years ago. Specific evidence of the earliest glaciations doesn't exist because moraines (ridges of unsorted, unstratified rock debris carried on or pushed in front of a glacier) formed by the early glaciers were destroyed by glaciers that followed later. Each time glaciers flowed down the mountain valleys they eroded the valley sides and bottoms, helping to straighten and deepen them, removing evidence of earlier glaciations.

Evidence of the last two major periods of ice accumulation is quite clear, however. The first of these two glacial periods is called the Bull Lake Glaciation. The Bull Lake advance began about 300,000 years ago and ended about 130,000 years ago. A few isolated remnants of moraines from the Bull Lake glaciers can be identified at various places in the park. They indicate that the amount of ice in the valleys then was equal to or greater than ice volume during the most recent period of glaciation.

After the Bull Lake glaciation came a warmer period that lasted about 100,000 years. The last major glacial episode, called the Pinedale Glaciation, began about 30,000 years ago when Earth's climate once again cooled. The Pinedale glaciers reached their maximum extent between 23,500 and 21,000 years ago. Most of the major valleys in the park were filled with glaciers during this time. One of the largest of the park glaciers, with a length of 13 miles (21 km), was in Forest Canyon just south of the high point of today's Trail Ridge Road. The largest glacier, about 20 miles long, was the ice flow that occupied the Colorado River Valley on the west side of the park. The ice in many of these glaciers reached thicknesses of 1,000 to 1,500 feet. The only glaciers found in the park today occupy locations that receive a large amount of snow blown across the mountain ridges into northeast-facing, shaded cirques where snow melts slowly during summer. None of these glaciers are remnants of Ice Age glaciers.

Between 15,000 and 12,000 years ago, the climate warmed and the glaciers rapidly disappeared. As the glaciers melted, the rocks they had carried were strewn along the edges and terminations of their paths, forming moraines, or ridges of rock debris. A terminal moraine, formed at the foot of a glacier, often creates a natural dam that obstructs the flow of winter runoff, creating lakes in which sediment and organic material accumulate. Over time, a moraine-dammed lake may evolve into a meadow. Many of the park's meadows, such as Horseshoe Park and Moraine Park, are examples of this process.

Points of Geologic Interest

Longs Peak is the highest peak in the park, cresting at 14,255 ft with a conspicuous flat summit. It is a prominent feature from many vantage points along roads in the park, and along many backcountry hiking trails. South of Estes Park on Highway 7, a roadside viewing area provides a fine view of the northeast face, a 1,000-foot sheer cliff of the glacial cirque headwall called The Diamond.

Trail Ridge Road takes visitors on a traverse back in time over the park's high mountain ridges. Here are remnants of the most ancient rocks in the park, recognizable by the marbled gray, white, and black bands of minerals in granular streaky gneiss and the darker, finer grained schist. The Silver Plume Granite is distinctive for its gray-tan and pink-red coloration and for the prominent feldspar crystals that sparkle in the sunlight.

Horseshoe Park is named for the glacial moraines that rim the valley in the shape of a horseshoe. A giant alluvial fan that spreads into the upper end of Horseshoe Park marks the catastrophic discharge from the failed Lawn Lake Dam on July 15, 1982, which sent a torrent of water and huge boulders down the Roaring Fork River to the valley floor.

Old Fall River Road is a one-way road from Endovalley to the Alpine Visitor Center. It crosses Chiquita Creek, where there is a good view of Hanging Valley. Geologists believe that this canyon and the Fall River Canyon were once on the same level. However, the carving action of the Fall River Glacier scraped the main gorge so deeply that the side canyon was left hanging high up on the wall. Across the creek, you can see pits in granite rock, ground out by the swirling waters of the glacier.

Glacier Gorge has one of the park's best examples of a classic glacier-carved, U-shaped valley, which is visible from Bear Lake and Fall River Valley. The sharp peak of The Spearhead in Glacier Gorge is a “horn”, a pyramidal spire that remains after glaciers carved cirques on three or more faces of the peak.

Moraine Park's long, wooded slope at its south edge is a classic example of the lateral moraine, rock rubble that forms at the side of a glacier. Close examination of the moraines along both north and south flanks of Moraine Park show deposits of the older Bull Lake Glaciation and the younger, more prominent Pinedale Glaciation.

Kawuneeche Valley is a long, broad glacial valley formed by water and ice erosion along a major fault zone. Looking south from Farview Curve, you can see the headwaters of the Colorado River (originally named the Grand River) meandering along it. Over the past several hundred thousand years, the valley has been widened and its walls steepened by several glaciers fed from the Never Summer Mountains across the valley and from the Milner Pass area. The Colorado gathers strength and flow volume here from snow melt before descending through Glenwood Canyon in Colorado, the former Glen Canyon in Arizona, and ultimately, the Grand Canyon to the Gulf of California.

Grand Ditch is a water diversion project located alongside the Never Summer Mountains that predates the establishment of Rocky Mountain National Park. Construction was begun in 1890 and completed in 1936. The 17 mi system delivers an average of 20,000 acre-feet of water annually over the Continental Divide at La Poudre Pass to the eastern plains of Colorado.

The Never Summer Mountains are in large part are roots of extinct volcanoes. Several thousand feet of volcanic rock eroded away; what remains today is granitic rock that are the remnants of the magma chambers below the volcanoes that erupted between 24 and 29 million years ago.

Numerous mining claims were staked in the late 1800s in the Never Summer Mountains (and elsewhere in the park). One of these sites is Lulu City (about 3 miles up the Colorado River Trail). Optimistic prospectors hoped for silver and gold. Rocky Mountain National Park’s location just beyond the Colorado Mineral Belt-- which produces gold, silver, tungsten, molybdenum, uranium, lead, and zinc-- obviously disappointed those prospectors but made possible the setting aside of this area as a national park that has no minerals of commercial value.

Conclusion

The relative ages of different rock units can be determined fairly simply by observing their stratigraphic relationships. The granite cuts across the gneiss and schist layers and their folds, indicating that the granite is the younger unit. In the same area, coarsely-crystalline pegmatite dikes truncate fabric in both the metamorphic rocks and the granite, proving that these are younger still. After a long period of erosion that planed a relatively smooth surface on the top of the granite, gneiss, and schist, magma was injected up through the basement and erupted as volcanic deposits on top of the older rocks. Most recently, the glacial moraines and tills were deposited atop the other rock types, making them among the youngest geological features in the park.

The grandeur of Rocky Mountain National Park is the culmination of many geologic events: the formation of the rocks through hundreds of millions of years, the repeated uplift of the mountains by continental tectonic forces, and millions of years of erosion by water and ice that sculpted the mountains into their present forms.

Appendix G. Compilation of Notes from Geoindicator Scoping Discussion

Glacial and Periglacial Geoindicators

Frozen Ground Activity

Background

Permafrost –permanently frozen soil-- influences natural and managed ecosystems, including forests, grasslands and rangelands, mountains and wetlands, and their hydrological systems. It is an agent of environmental change that may have profound effects on ecosystems and human developments. Permafrost may enhance further climate change by the release of carbon and other greenhouse gases during thawing. Permafrost can result in serious and costly disruptions from ground subsidence, slope failure, icings, and other cryogenic processes. The freezing and thawing of soils and surficial materials and the consequent ground changes are natural processes controlled by climatic conditions, and can be modified by human actions in and around settlements and engineering works.

Permafrost is present in 13% of the world's soils. Where there is extensive seasonal freezing and thawing of soils, a wide range of processes lead to a variety of sensitive periglacial features that can be found around glaciers, in high mountains (even at low-latitudes) and throughout polar regions. Permafrost areas are characterized by a wide range of slow downslope movements involving creep, such as rock glaciers and gelifluction, and by more rapid landslides and snow avalanches (see slope failure geoindicator).

The thickness of the active layer, the zone of annual freezing and thawing above permafrost, determines not only the overall strength of the ground but also many of the physical and biological processes that take place in periglacial terrains. Frost heaving is a physical process associated with near surface winter freezing and can displace buildings, roads, pipelines, drainage systems, and other structures. Frost cracks are steep fractures formed by thermal contraction in rock or frozen ground with substantial ice content. They commonly intersect to create polygonal patterns or patterned ground.

Points of Discussion

Frozen ground activity (frost heave and gelifluction) is a major geologic process active in Rocky Mountain National Park. Patterned ground occurs in high alpine areas (stone polygons and stone stripe features). These features are thought to form from frost heave and frost cracking and are extremely sensitive to human disturbance. Visitors have access to patterned ground along the Tundra World Nature Trail. The park has limited parking access and asks visitors to fan out when walking across these surfaces to minimize disturbance of these features. Human trampling of patterned ground is not thought to be a problem at this time. However, there is no monitoring of human impacts on this resource.

Solifluction lobes and terraces, and gelifluction features are also present in the park. Gelifluction occurs on slopes where daily and seasonal cycles of freezing and thawing slowly moves soil downslope over thousands of years. Raup (1996) concluded that most of the soil movement occurred during periods of maximum glaciation, the last being 20,000 years ago.

Landscapes with active gelifluction can create significant engineering and maintenance problems for facilities, roads, trails, and septic systems. For example, the sections of the Trail Ridge Road which cross slopes with gelifluction activity have significant and recurring maintenance problems. In these areas, the combination of building the road across gelifluction terrain and loading the slope with roadfill material may have changed the rate of movement. While a few roads and trails can locally affect frozen ground activity, this process does not appear to be a problem overall for the park facilities and developments. Future park developments, roads and trails need to consider frozen ground issues. The rates of gelifluction have fluctuated throughout geologic time and some change is expected. Assessment of the depth, thickness of the permafrost and monitoring the rate of creep or movement would be useful to park management and maintenance. If creep rates change overtime, the park can evaluate what potential effects might occur to park infrastructure and resources.

For long-term changes related to this geoindicator, the park should track several regional studies such as work at Niwot Ridge Long Term Ecological Research Program in Colorado (http://www.colorado.edu/mrs/).

The treeline or forest/tundra ecotone is an important marker for understanding paleoclimates. Treeline position may be a better indicator of climate change than monitoring glacier fluctuations. However vegetation responds slowly to climate change. It would be useful to determine the location of former treeline/tundra ecotone and evaluate what controls its position in the park.

Human influence on these types of processes is low. However, soil creep associated with annual freeze and thaw cycles can cause significant problems with park roads, trails, and buildings which result in high long-term maintenance costs in specific areas of the park. Management significance is considered moderate.

Glacier and Firn Field Fluctuations

Background

Glaciers grow or diminish in response to natural climatic fluctuations. They record annual and long-term changes and are practically undisturbed by direct human actions. Their capacity to store water for extended periods exerts significant control on the surface water cycle. Glacier advances, the length of mountain glaciers and their ice volume has decreased throughout the world during the past century or two, providing strong evidence for climate warming.

Changes in glaciers can exert profound effects on the surrounding environment. The advance and retreat of mountain glaciers creates hazards to nearby human structures and communities through avalanches, slope failure, and catastrophic outburst floods from ice and moraine-dammed lakes. The location of the terminus and lateral margins of ice and rock glaciers also exerts an influence on nearby physical and biological processes.

Points of Discussion

Interest in long-term changes in glaciers at Rocky Mountain National Park was initiated by the Interpretive Division. A Geoscientist-in-the-Park was hired to address the question of whether glaciers in the park are retreating. The geoscientist developed six informal technical reports interpreting glaciers and glacial features in the park. Currently there is no inventory of glaciers and firn fields in the park. Glaciers and firn fields are both a visual resource as well as a physical feature to explore. Hiking in these areas can pose a safety issue to park visitors and maintenance of facilities (outhouses) around these features in high alpine areas can be challenging.

Glaciers in the park are probably not a significant source of water to the park or front range ecosystems and communities. Runoff in Colorado is produced primarily by melting of the winter snowpack and summer thunderstorms (Pitlick, 1988). The USDA measures water content of the snow pack at selected localities each winter. It would be useful to determine the contribution of water from melting snowfields and glaciers to annual runoff in park streams.

Glaciers and firn fields are important both aesthetically and scientifically to Rocky Mountain National Park and are rated high for its significance to ecosystems. Humans have a moderate influence on this resource and the significance to park management was also rated as moderate due to potential floods from ponded meltwater.

Lake Ice (Ice Phrenology)

Background

This is a new geoindicator identified by the scoping group. This geoindicator was also identified at a recent international meeting on the application of geoindicators at Gros Morne National Park, Canada in September 2001. Ice phrenology refers to periodic ice phenomena related to climate. In particular the first formation of lake or sea ice and the first break up or melt. Ice phrenology provides an early warning monitoring system for climate change. Monitoring when ice first forms and when it breaks up on larger lakes will provide baseline information on which to evaluate change.

Points of Discussion

This geoindicator is considered high for its importance as a natural process in the park, human influence (global climate change) and management significance.

Arid and Semi-Arid Geoindicators

Wind Erosion

Background

The action of wind on exposed sediments and friable rock formations causes erosion, and entrainment of sediment and soil particles, and also forms and shapes sand dunes and other landforms. Wind can reduce vegetation and expose subsurface deposits and plant roots. Wind erosion is a natural phenomena, but the surfaces it acts upon may be made more susceptible to wind erosion by human actions, especially those activities such as cultivation and over-grazing, that result in the reduction of vegetative cover.

Wind erosion of sediment occurs in only limited areas of the park. This process is only significant in areas that are exposed to strong winds and lack vegetation or abundant rock fragments. However, in Rocky Mountain National Park, wind is an important mechanism for redistributing winter snowfall from the west side of the mountains to the heads of valleys on the east side. East facing slopes sit in a slight rain shadow of the continental divide and west winds during the winter redeposit and supply snow to the east facing glaciers and snowfields.

Humans have relatively low to no influence on this process. This geoindicator while important as a supply mechanism for snow to east facing glaciers, is considered to have only moderate management significance.

Airborne Sediment and Deposition

Background

The original dust storm geoindicator did not accurately fit the park setting and was altered to the airborne sediment and deposition geoindicator below.

Local, regional and global weather patterns can be strongly influenced by accumulations of dust in the atmosphere. Fine particulate matter in the atmosphere creates a nucleus for precipitation and snow. While, dust storms are a mechanism to transport sediment and are natural events, the amount of sediment available for transport may be increased by human disturbances such as overgrazing, farming, or removal of vegetation. Dust storms can remove large quantities of surface sediments and topsoil. Material picked up from other continents can be transported in the atmosphere across the oceans and deposited locally. In China, farming of marginal lands has created significant soil disturbance. As a result, dust storms in that region are much higher than historically and can potentially affect the amount of fine particulate matter in the atmosphere at a global scale. Land use, primarily farming, on both the east and west side of the park and development in the Front Range urban corridor are also a local sources of particulate matter to the park.

Points of Discussion

The Air Quality Division of the National Park Service currently monitors an air quality station in the park. Air clarity is measured with a transmissometer, but the instrument doesn't differentiate between fog, smoke, or dust particles.
Current monitoring does not monitor deposition of air born dust from outside the park boundaries. Increases in dust particles may impact air clarity and viewshed, and affect nitrate deposition and precipitation amounts in the park.

Deposition of airborne sediment is not considered an ecologically important process in the park and the park through its management cannot affect a change in dust production or distribution from local or global sources. This geoindicator was considered of moderate significance to park management. Future increases in particulate matter could hinder the park's controlled burning program. Excess airborne dust could prohibit controlled burning at times if smoke generated by the burns would cause air clarity standards to be exceeded. This geoindicator will have a higher significance to the park if this occurs. Deposition of airborne nitrates are a significant concern to the park and discussed under the water quality geoindicator.

Groundwater Geoindicators

Groundwater Quality

Background

Groundwater is important for human and animal consumption, and changes in quality can have serious consequences. It is also important for the support of habitat and for maintaining the quality of base flow to streams. The chemical composition of groundwater is a measure of its suitability as a source of water for human and animal consumption, irrigation, and for industrial and other purposes. It also influences ecosystem health and function, so that it is important to detect early warnings of change both in natural systems and resulting from pollution.

Points of Discussion

In the park, human activities affecting the groundwater quality are limited. There are only a few private inholdings in the park, some gas-lines, maintenance yards, and the only septic fields are at the Alpine Visitor Center. Groundwater monitoring is limited to water level measurements in groundwater wells used for drinking water. Baseline groundwater quality data should be collected.

Human impacts on groundwater quality may occur if there is a specific point of release. Groundwater quality is considered moderate for human influence and management significance.

Groundwater Level and Springs

Background
Groundwater is a major source of water in many regions, and in arid regions it is generally the only source of water. There are natural changes in groundwater levels because of climate change (drought, pluvial episodes), but the main changes are due to human extraction. Groundwater is replenished from precipitation and from surface water, but the rate of withdrawal by humans may exceed the rate of natural recharge, leading to reduction of the resource. In alluvial plains, reduction in streamflow by pumping reduces the rate of natural recharge to aquifers. The availability of clean water is of fundamental importance to the sustainability of life. It is essential to know how long the resource will last and to determine the present recharge rates.

Points of Discussion
Springs are a natural feature in the park. Some staff observed dead trees in the boulder field on Longs Peak near old spring areas. It is speculated that locations of springs may have changed in the past 30-40 years and that the decrease in spring flow killed the trees.

The Grand Ditch is the largest diversion in the park and captures water from the upper Colorado River in the Kawuneeche Valley. Hydrologic analysis has shown that the water diverted by the Grand Ditch has significantly altered streamflow regimes in the upper Colorado River (see streamflow geoindicator). Water level monitoring by Woods (2000) indicated that in mid- to late summer, the groundwater levels in wetlands in the valley bottom responded to changes in river stage up to 650 ft from the Colorado River (Woods, 2000). Groundwater levels in riparian wetlands are also influenced by hillslope runoff, summer rainfall, and recharge from beaver ponds. Due to the channel geometry of the upper Colorado River (high width-to-depth ratio), large changes in streamflow from water diversions result in only relatively small changes in water stage. Woods (2000) determined that reduced summer flows on the mainstem caused by water diversions decrease groundwater levels about 4 – 8 inches. He also found that water diversions caused substantially reduced tributary streamflows and groundwater flow during the summer and can be directly related to reduction in groundwater levels in some toeslope wetlands and peatlands. Woods (2000) measured as much as a 15.7 inches drop in water level in toeslope wetlands near Lost Creek and a drop of more than 19.7 inches in two out of three peatlands near Red Creek during summers with low rainfall. He concluded that these peatlands and wetlands are highly susceptible to reduction in flows from the Grand Ditch. The effects of lowered groundwater levels in the Kawuneeche Valley include reduced recruitment of willows, apparent increase in the abundance of dryland exotic plants and net loss of carbon from selected peatlands.

Groundwater extraction for drinking water occurs at a limited number of sites in the park and extraction is not impacting groundwater levels (see groundwater quality geoindicator). However, groundwater levels should be monitored in conjunction with baseline groundwater quality monitoring. This geoindicator was rated low for its importance for natural processes, human influence and moderate for management significance.

Surface Water Geoindicators

Lake Levels

Background

The historic fluctuations in lake levels provides a detailed record of climate changes on a scale of ten to a million years. Lakes are dynamic systems that are sensitive to local climate and to land-use changes in the surrounding landscape. Some lakes receive their water mainly from precipitation, some are dominated by rainfall and snowmelt runoff from drainage networks, and others are controlled by groundwater systems. The areal extent and depth of water in lakes are indicators of changes in climatic parameters such as precipitation, radiation, temperature and wind speed. Where not directly affected by human actions, lake level fluctuations are excellent indicators of drought conditions. Lakes can also be valuable indicators of near-surface groundwater conditions.

Points of Discussion

There are both perennial and ephemeral lakes (e.g., Sheep Lakes), and several reservoirs (e.g., Long Draw and Shadow Mountain) in Rocky Mountain National Park. At Sheep Lake, fluctuations in lake level affect the formation and availability of evaporites used by big horned sheep and other wildlife. Lake level fluctuations that might cause a change in the supply of evaporites for wildlife would be a management concern. The park does not currently monitor lake levels.

Except for reservoirs where water levels are managed, human activity has little influence on lake levels and was rated low. Management significance was rated as moderate because of the importance of maintaining this resource for big horned sheep and other wildlife.

Surface Water Quality

Background

Water is essential to all living organisms. The water quality of a lake, river, pond or wetland is determined by interactions with soil, transported solids (organics, sediments), rocks, groundwater and the atmosphere. Surface water quality may also be significantly affected by agricultural, industrial, urban and other human actions, as well as by atmospheric inputs. Pollution of natural bodies of surface water is widespread because of human activities, such as disposal of sewage and industrial wastes, land clearance, deforestation, use of pesticides, mining, and hydroelectric developments.

Points of Discussion

The park's natural resources are affected by industrial airborne pollution, such as nitrates, from the urban corridor along the eastern slope of the Front Range. Nitrogen saturation in Rocky Mountain National Park and episodic acidification in areas near the park have been documented by the U.S. Geological Survey. Over the past two decades, scientists have documented a shift in ecosystem dynamics from a nitrogen-limited system to a nitrogen-saturated system as a result of anthropogenic nitrogen. Cumulative evidence from multiple studies in Rocky Mountain National Park (Loch Vale) and adjacent areas along the Colorado Front Range (Niwot Ridge) strongly suggest that current levels of nitrogen deposition are currently altering terrestrial and aquatic ecosystems on the eastern side of the mountains (http://www.aqd.nps.gov/ard/epa/index.htm). Concern over the increase in nitrogen availability above current levels may lead to changes in the alpine plant species composition (shift from forbs to grassland dominated communities). Long term changes in the biochemical cycle can result in a shift in alpine vegetation with lower nutritional value and will ultimately affect the park's wildlife species. The park is concerned about the potential long-term change in the nutritional value of plants used for foraging by big horn sheep, ptarmigan, and other wildlife species.

Pollution sources from the east side of the Colorado Front Range can be linked to increases in nitrogen in the soils, streams, lakes and spruce trees in the park, as well as, changes in lake diatom community composition over time (Barron, et al 2000). Based on evidence from these studies, the park service is petitioning the EPA to set higher air quality standards. More specifically, lower target loads for wet (rain and snow) nitrogen deposition in the Colorado Front Range. Monitoring for this type of pollution will be considered in the Rocky Mountain National Park inventory and monitoring program

This geoindicator rated high for geologic process, human influence and management significance.

Stream Channel Morphology

Background

Streams are dynamic and can be associated with rapid changes in landforms, such as channel shape, bedforms, gravel bars, flood terraces and stream banks. Stream channel dimensions (width, depth, meander wavelength, and gradient), channel pattern (braided, meandering, straight) and sinuosity (a measure of pattern curvature) are significantly affected by changes in streamflow and sediment discharge. Significant and rapid changes in stream dimensions, discharge and pattern may reflect human influences such as water diversion and increased sediment loads resulting from land clearance, road construction, farming, or forest harvesting. Streams are also responsive over a longer time period to climatic fluctuations and tectonics.

Points of Discussion

The diversion of water from the Kawuneeche Valley has significantly altered streamflow over the past 100 years and substantially changed the wetlands and channel morphology of the upper Colorado River. Cooper et al (2000) noted that "the effect of the reduction in high flows and sediment transport capacity is apparent in terms of channel narrowing and development of mid-channel bars in the Colorado River."

Human alteration of the upper reaches of Roaring River Valley resulted in a devastating debris flow when a dam failed catastrophically in 1984 (see stream sediment storage and load geoindicator for a more detailed description). The dam failure resulted in extensive scouring of the channel and significant and long-term changes in channel morphology.

The stream that flows through the Hidden Valley Ski Area was first impacted in 1954 when the first ski lift and parking area were developed. The parking lot buried the stream and a wetland. In the 1960s, a lodge was added and the total length of stream culverted was about 400 feet. In the future, the stream channel and wetland will be restored when the ski area, buildings, and parking lot are removed. Most of the buildings have been demolished in the Hidden Valley Ski Area and the Environmental Assessment has been reviewed by the public.

The park has inventoried 210 check dams in the park. Removal of check dams will alter streamflow and sediment transport, and may change the channel morphology downstream. The channels downstream from these check dams should be monitored.

Changes in channel morphology rated high in the streams mentioned above. Other park streams are of only moderate concern. This geoindicator rated high for significance as a geologic process in the park, human influence and management significance.

Streamflow

Background

Streams are an important geoindicator because streams respond rapidly to changes in sediment load, precipitation, and runoff. Stream systems also play a key role in the regulation and maintenance of biodiversity. Changes in streams and streamflow are indicators of changes in watershed dynamics and land use. Natural variations in streamflow predominate, but can be strongly modified by human actions (dams, reservoirs, irrigation, and diversion for use outside the watershed).

Points of Discussion

Surface water processes occur all year in Rocky Mountain National Park and have a long-term influence on the park's landscape. They are also among the most dynamic geologic processes in the park. Park streams are dominated by a spring snow-melt flow regime and generally do not experience the extremely large annual peak flows common in rain-dominated systems at lower elevations. Melting of the snowpack is a major hydrologic event during the year. Studies in Loch Vale watershed indicate that over 60 % of the annual streamflow typically occurs during the summer months in June and July. As a result, the bankfull discharge and large recurrence interval (RI) flows (50-100 year RI) are similar in magnitude. However, extreme flood events driven by rainfall have occurred. Flash flooding can also occur in the park but is a rare phenomenon.

While it was in operation, the Hidden Valley Ski Area captured and diverted all the stream flow in the watershed for making artificial snow. At the ski area, the park removed 100,000 gallon tanks that were used to store the water. Endangered greenback cutthroat trout occupy the channel downstream of this site. The human alteration of streamflow and culverting of the stream channel (see channel morphology geoindicator) caused significant impacts to aquatic habitat within and downstream of the ski resort.

The Grand Ditch is the largest diversion in the park and captures the flow of eleven headwater tributaries in the Colorado River basin. The ditch is 25 km long and intercepts 29% of the total annual runoff to the upper Colorado River. Woods (2000) found that although the instantaneous annual peak flows of all recurrence intervals have been reduced, the greatest impacts are on the more frequent and lower magnitude peak flows which have been reduced by as much as 55%. While the same amount of water is diverted annually, the proportion of the total runoff diverted from the upper Colorado River can range from 20 % in years with a large snow pack to 40% in years with a small snow pack. Woods (2000) estimated that during July and August about half of the total runoff never reaches the upper Colorado River and is diverted for urban and agricultural use. The Colorado River also has experienced about a 40 % reduction in the 3-, 7- and 30- day low flows.

The frequency of overbank flooding and channel maintenance flows have been reduced by about half. The Grand Ditch has significantly altered streamflow, channel morphology, and wetlands in the Kawuneeche Valley for the last century. Water captured by the Grand Ditch is prevented from reaching the upper Colorado River and is diverted over the continental divide into the Cache la Poudre River to supply water to communities and agriculture on the eastern slope of the Front Range. Impacts from the Grand Ditch on the park's natural resources is a significant concern to park management and the park has a long-term interest in resolving the water rights issues in the Kawuneeche Valley.

In addition to water diversions, several reservoirs in the park regulate streamflow to park streams. This geoindicator is rated high for geologic process, human influence and management significance.

Stream sediment storage and load

Background

Sediment load partly determines channel shape and pattern. Changes in sediment yield reflect changes in basin conditions, including climate, soils, erosion rates, vegetation, topography and land use. Fluctuations in sediment load or (sediment discharge) affect many terrestrial and coastal processes. Ecosystems may also respond to changes in sediment transport because nutrients are transported together with the sediment load. For example, to reproduce effectively, salmon and trout need clean gravel streambeds for spawning and egg survival. Silt and clay deposited in and on the gravel streambed during winter storms or resulting from excessive upstream erosion can bury and destroy these spawning beds. Periodic high discharges, such as the bankfull flow, transport streambed sediment and also flush silt and clay from spawning gravels. Stream deposits also represent huge potential sinks for, and sources of, contaminants. Stream sediment storage and load is strongly influenced by human actions, such as in the construction of dams and levees, timber harvesting, road building and farming in drainage basins.

Points of Discussion

An excellent example of human influence on sediment transport and deposition in the park can be observed at the alluvial fan deposited by the Lawn Lake dam failure and flood. The dam was built in 1902 to provide irrigation water to Loveland, Colorado. On July 15, 1982, the Lawn Lake Dam catastrophically failed in the upper Roaring River Valley and released water held in the reservoir down the channel. Within minutes, floodwaters scoured sand, gravel and boulders from the Roaring River Valley and deposited the sediment downstream on an alluvial fan where the steep, confined Roaring River channel joins the broad, flat Fall River valley. Floodwaters continued downstream and flooded downtown Estes Park.

Changes in streamflow due to diversion of water has altered sediment transport in some park streams. Cooper et al (2000) observed that the reduced frequency of overbank flows due to the water diversions have resulted in reduced sediment transport capacity.

The park has inventoried a couple hundred check dams on park streams and is in the process of removing them (see channel morphology geoindicator).

The stream sediment storage and load geoindicator is rated high for geologic process, human influence, and management significance.

Wetlands extent, structure and hydrology

Background

Wetlands are areas of high biological productivity and diversity. They provide important sites for wildlife habitat. Wetlands along stream channels can serve as flood buffers, and also affects local hydrology by acting as a filter, sequestering and storing heavy metals and other pollutants. Wetlands also can act as a carbon sink, storing organic carbon in waterlogged sediments and can also be a carbon source, when it is released via degassing during decay processes, or after drainage and cutting, as a result of oxidation or burning. Globally, peatlands have shifted over the past two centuries from sinks to sources of carbon, largely because of human exploitation.

Wetlands develop naturally in response to morphological and hydrological features of the landscape. Their evolution can be affected by external factors such as climate change, landscape processes (e.g. coastal erosion) or human activity (draining, channeling of local rivers, surface-water and groundwater extraction and surface-water impoundment, forest clearance).

Points of Discussion
In the park, impacts to wetlands have been documented from the diversion of surface water flow for agriculture or urban use. Woods (2000) documented that diversion of water by the Grand Ditch has substantially lowered water levels in some peatlands and wetlands in the Kawuneeche Valley. He found evidence that the rate of carbon loss in peatlands in the Kawuneeche Valley may not be sustainable in the long-term and if these conditions persist may ultimately lead to disappearance of these peatlands. Refer to the discussion of the impacts of the Grand Ditch on wetlands in the groundwater level and spring activity geoindicator.

Beavers are also a major influence on the hydrology and geomorphology of wetland ecosystems. They create dynamic and complex wetland habitats. Data indicate that Beaver populations have declined in Rocky Mountain National Park since the park's establishment in 1915. Park staff noted that the absence or low population of beavers may be another critical issue affecting the wetlands and riparian areas in the Kawuneeche Valley.

The park is concerned with anthropogenic disturbance of wetlands. To that end, the park has focused on wetland issues and mitigation to ensure little or no human impacts occur on these fragile resources. At Sprig Lake and MacGraw Ranch elevated boardwalks have been installed to protect and maintain wetland functions while still allowing access to park visitors.

This geoindicator is rated high for geologic process, human influence and management significance.

Tectonics and Gravity Geoindicators

Slope Failure

Background
Slope failures are forms of mass wasting (rock falls, landslides, debris flows, slumps, soil creep) as opposed to fluvial (water) erosion. Slope stability is dependent on slope gradient or steepness, water content and soil water pressure, type of earth material, structural properties, and local environmental factors such as ground temperature. Slope failures may take place suddenly and catastrophically, resulting in debris torrents, snow avalanches, rock falls, slides and debris flows. Or slopes failure may result in a slow downslope movement of material (slides slumps, earthflows, complex landslides and creep). There are innumerable small to medium-size slope failures that cumulatively impose costs to society as great or greater than the large infrequent

catastrophic landslides that draw so much attention. Locally landslides may destroy terrestrial and aquatic habitats. For example, debris flows involve rapid movement of large volumes of water charged soil, rock and woody debris. They can denude hillslopes, scour stream channels, and deposit large volumes of sediment and block streams. Landslide hazard is determined through a risk analysis of the probable recurrence (how often) and potential volume of material, and identifying what resources are at risk in a slope failure. Human activity such as developments, timber harvesting, and road building can change the rate, frequency, spatial distribution and size of the failure.

Points of Discussion

The Grand Ditch cuts into the mid- to upper slopes of the Never Summer Range and creates a landslide risk for the upper Colorado River from undercutting the hillslope. Landslide material deposited in the Grand Ditch is cast downslope when the ditch is cleaned annually.

Debris flows and large slump features have been identified in the back country. Rockfall is a continuous and pervasive process across the park and affects maintenance of roads and trails. Rockfall also occurs in the upper parts of all valleys in fairly remote areas. Periodically, snow avalanches impact roads and trails.

A landslide map of Colorado by Colton (1976) is very general and based on 2^{o} sheets. This map could provide a general landslide map for the park. Landslide information is also included in Braddock and Cole's (1990) geologic map of Rocky Mountain National Park. However, a more detailed slope failure map and a snow avalanche risk map for the park would be useful for park planning and maintenance. Snow avalanche areas in the park may have been mapped by other agencies or research organizations (INSTAAR or Colorado Avalanche Information Center).

Human influence on slope failure in the park is rated as moderate but rated high as an important geologic process in the park and for management significance.

Seismicity

Background

Crustal movements along faults cause earthquakes. Earthquakes are predominantly natural events. However, shallow-focus seismic tremors can be induced by human actions (extracting water, gas, petroleum; mining or quarrying activities). Underground explosions, particularly for nuclear testing, can also generate seismic events. Earthquakes can result in marked temporary or permanent changes in the landscape. Surface effects include uplift or subsidence, surface faulting, landslides and debris flows, liquefaction, ground shaking, and tsunamis.

Points of Discussion

Rocky Mountain National Park is located near the Front Range Fault. A large earthquake near the park could cause rockfall and landslides, and changes in spring and streamflow. Historically the largest earthquake in Colorado was a magnitude 6.6 west of Ft. Collins. While earthquakes may affect park resources, the recurrence interval of damaging earthquakes is on the order of hundreds of years. There is no human influence on seismicity and management significance is rated low.

Surface Displacement

Background

Surface displacements are natural phenomena associated with plate movements, glacial rebound, and faulting, but human activities such as extraction of groundwater, oil, and gas can also induce surface displacement. Most surface displacements have but minor effects on landscapes and ecosystems. However, there are exceptions, such as where drainage channels are suddenly displaced by faults, or where seismically-induced uplift raises intertidal ecosystems above sea-level. Moreover, extraction of fluids beneath urban areas can induce land subsidence and cause flooding, especially of coastal communities near sea-level. Subsidence can damage buildings, foundations and other built structures.

Points of Discussion

Potential for surface displacement in the park is low and as a result it rated low as a natural process, human influence and management significance in the park.

Soil Geoindicators

Soil Quality

Background

As one of earth's most vital components of the ecosystems, soil is essential for the continued existence of life on the planet and has a major influence on terrestrial ecosystems. Soils continuously recycle plant and animal remains and are a source of plant nutrients. Soils determine the agricultural production capacity of the land and are a major support system for human life. Soils buffer and filter pollutants, store moisture and nutrients, and are important sources and sinks for CO_2, methane and nitrous oxides. Soils also provide an archive of past climatic conditions and human influences.

Soils can be degraded or enhanced by both natural processes and human activities. Human activities influence soil properties by causing increased compaction and acidification from inorganic fertilizers and acid rain. Soil degradation is one of the largest threats to environmental sustainability.

Points of Discussion

An Order 2 soil survey was completed in the lower elevation areas of the park and an Order 3 soil survey completed for the other areas of the park in 1998 by the Natural Resource Conservation Service.

In general the soils comprise a relatively thin veneer in the park. A soil survey of the park has just been completed. The primary human influence to soil quality in the park is from an engineering perspective. Compaction of soils has occurred around the Hidden Valley Ski Resort, along roads and trails and parking lots. Impacts to soil quality are localized in the park and this geoindicator was rated low for its significance as a geologic processes, human influence and park management.

Soil and Sediment Erosion (Water)

Background
Soil erosion is an essential factor in assessing ecosystem health and function. Removal of soil occurs primarily through fluvial processes (erosion by water) such as sheet, rill, and gully erosion. Soil erosion reduces the levels of the basic plant nutrients and decreases the diversity and abundance of soil organisms. Sediment eroded from a watershed and delivered to a stream can degrade water supplies and provide a transporting medium for a wide range of chemical pollutants. Increased turbidity due to fine sediment loads (silt- and clay-sized material) may adversely affect aquatic organisms such as benthic algae, corals and fish. Erosion is a fundamental and complex natural process that is strongly modified (generally increased) by human activities such as land clearance, agriculture, forestry, construction, surface mining and urbanization.

Points of Discussion
In the park, accelerated soil and sediment erosion is isolated to a few places in the park. Existing and social trails cause increased erosion especially on south facing slopes in the montane zone. High natural erosion rates can be exacerbated by human activities, such as road and trail building and horseback riding in riparian areas, and lead to impaired resources. Soil and sediment erosion rated low for its importance as a geologic process in the park and rated moderate for human influence. Maintenance of trails is a management concern and the management significance is considered moderate.

Other Geoindicators

Sediment Sequence and Composition

Background
The chemical, physical and biological character of aquatic sediments can provide a finely resolvable record of environmental change, in which natural events may be clearly distinguishable from human inputs. Lakes, wetlands, streams, floodplains, estuaries, reservoirs, fjords, shallow coastal seas and other bodies of marine or fresh water commonly accumulate deposits derived from bedrocks, soils, and organic remains within the drainage basin, though fine particles can also be blown in by winds from distant natural, urban and industrial sources. Of particular value in determining long-term data on water chemistry are the remains of aquatic organisms (e.g. diatoms, chrysophytes, chironomids, and other algae and invertebrates) which can be correlated

with various environmental parameters. In addition, fossil pollen, spores, and seeds reflect past terrestrial and aquatic vegetation. These aquatic deposits may preserve a record of past or on-going environmental processes and components, both natural and human-induced, including soil erosion, air-transported particulates, solute transport, and landsliding. Sediment deposits can, thus, provide an indication of the degree and nature of impact of past events on the system, and a baseline for comparison with contemporary environmental change.

Points of Discussion

Quaternary stratigraphy for the Roaring Valley River is currently being mapped from sediments exposed by channel erosion during the catastrophic failure of the Lawn Lake dam. Information recorded in wetlands, lakes and marshes would provide a perspective of fire history, ecotones, and paleo-ecology in the park. Human influence on this geoindicator is low. This geoindicator is considered high for its importance as a geologic process and its management significance.

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